ESTCP
Cost and Performance Report

(MM-0416)

Demonstration of Synthetic Aperture Radar and Hyperspectral Imaging for Wide Area Assessment at Pueblo Precision Bombing Range #2, Colorado

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ACRONYMS AND ABBREVIATIONS

AGL	above ground level
ASR	Archive Search Report
BSQ	band sequential
BT3	Bomb Target 3
BT4	Bomb Target 4
CASI	compact airborne spectrographic imager
CCD	charged coupled device
CERCLA	Comprehensive Environmental, Response, Compensation and Liability Act
cm	centimeter(s)
CNR	clutter-to-noise ratio
DARPA	Defense Advanced Research Projects Agency
dB	decibels
DEM	digital elevation model
DoD	Department of Defense
DSB	Defense Science Board
ESTCP	Environmental Security Technology Certification Program
FAR	false alarm rate
FLBGR	Former Lowry Bombing and Gunnery Range
FOPEN	foliage penetration
FOV	field of view
FUDS	Formerly Used Defense Sites (program)
GIS	geographic information system
GLT	geographic lookup table
GPS	global positioning system
HSI	hyperspectral imaging
IFOV	instantaneous field of view
IMU	inertial measurement unit
IR	infrared
km	kilometer(s)
LiDAR	light detection and ranging

µm	micrometer
MEC	munitions and explosives of concern
MHz	megahertz
MMRP	Military Munitions Response Program
MNF	minimum noise fraction
MNR	multiplicative noise ratio
MRA	Munitions Response Area
mrad	millirad
NASA	National Aeronautics and Space Administration
NEσ0	noise equivalent backscatter
nm	nanometers
PBR	Precision Bombing Range
Pd	probability of detection
POI	point(s) of interest
POS	position and orientation
RCS	radar cross section
RGB	red-green-blue
RMSE	root mean square error
ROC	receiver operating characteristic
RTK GPS	real-time kinematic GPS
SAR	synthetic aperture radar
SNR	signal-to-noise ratio
SWIR	short-wave infrared
UHF	ultra-high frequency
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
W	watts
WAA	wide area assessment

ACKNOWLEDGEMENTS

Demonstration of Synthetic Aperture Radar and Hyperspectral Imaging for Wide Area Assessment at Pueblo Precision Bombing Range #2, Colorado, Cost and Performance Report provides an analysis of the cost of the demonstration and summarizes the performance in terms of the acquisition, processing, analysis, and interpretation of high airborne synthetic aperture radar (SAR) and hyperspectral imaging (HSI) data for wide area assessment (WAA) at the former Pueblo Precision Bombing Range #2 in Colorado. The work was performed by Sky Research, Inc. of Oregon, with Dr. John Foley serving as principal investigator.

Funding for this project was provided by the Environmental Security Technology Certification Program (ESTCP) Office. This project offered the opportunity to examine advanced airborne methods as part of the Department of Defense's (DoD) efforts to evaluate WAA technologies for the efficient characterization and investigation of large DoD sites.

We wish to express our sincere appreciation to Dr. Jeffrey Marqusee, Dr. Anne Andrews, and Ms. Katherine Kaye of the ESTCP Program Office for providing support and funding for this project.

We would also like to acknowledge and thank our partners on this project: Duke University, SIG, User Systems, and Arlen Schmidt for their work on the SAR data processing and analysis for this project and HyVista for data collection, processing and analysis of HSI data.

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Munitions and explosives of concern (MEC) contamination is a high priority problem for the Department of Defense (DoD). Recent DoD estimates of MEC contamination across approximately 1,400 DoD sites indicate that 10 million acres are suspected of containing MEC. Because many sites are large in size (greater than 10,000 acres), the investigation and remediation of these sites could cost billions of dollars. However, on many of these sites only a small percentage of the site may in fact contain MEC contamination. Therefore, determining applicable technologies to define the contaminated areas requiring further investigation and munitions response actions could provide significant cost savings. Therefore, the Defense Science Board (DSB) has recommended further investigation and use of wide area assessment (WAA) technologies to address the potential these technologies offer in terms of determining the actual extent of MEC contamination on DoD sites (DSB, 2003).

This report describes the cost and performance for the demonstration of two WAA technologies: synthetic aperture radar (SAR) and hyperspectral imaging (HSI). These two high-airborne sensor technologies were demonstrated at Pueblo Precision Bombing Range (PBR) #2 in Otero County, Colorado (Foley et al., 2007a, 2007b). Two additional high-airborne sensor technologies―light detection and ranging (LiDAR) and orthophotography―were also demonstrated at Pueblo PBR #2 (Foley, 2008), and the use of SAR and HSI as WAA technologies were evaluated both as standalone sensor technologies as well as members of a WAA sensor suite.

1.2 OBJECTIVES OF THE DEMONSTRATION

As WAA technologies, SAR and HSI are not designed to detect individual or low-density MEC contamination but rather to detect and map former high-density regions, such as bombing targets. The SAR demonstration was conducted to determine the utility of the dataset to detect metal, such as munitions, bomb fragments, tail fins, and other surface metal associated with prior military training activity. The HSI demonstration was conducted to determine the utility of this dataset for SAR false alarm mitigation, detection of surface metal targets, and detection of target features. Detection of surface metal objects was attempted through identification of spectral signatures of sufficient spectral contrast with background signatures. Detection of target features and other large munitions-related features was evaluated through identification of secondary indicators of MEC contamination such as ground disturbance, vegetation stress and composition, and exposed subsoil patterns.

1.3 REGULATORY DRIVERS

The United States Army Corps of Engineers (USACE) is the lead federal agency under the Formerly Used Defense Sites (FUDS) program. USACE administers the FUDS Military Munitions Response Program (MMRP) using DoD investigation and cleanup methods based on the United States Environmental Protection Agency (USEPA) Comprehensive Environmental, Response, Compensation and Liability Act (CERCLA) process.

1.4 STAKEHOLDER/END USER

The Environmental Security Technology Certification Program (ESTCP) initiated a WAA pilot program in 2005 that included the former Pueblo PBR #2 as an initial demonstration site. This SAR and HSI demonstration, begun in 2004 and expanded in 2005, was folded into the pilot program. As part of this program, ESTCP managed the stakeholder issues. ESTCP used a process to ensure that information generated by the high airborne, helicopter, airborne, and ground validation surveys was useful to a broad stakeholder community (e.g., technical project managers; federal, state, and local governments; and other stakeholders).

1.5 DEMONSTRATION RESULTS

A primary objective of this demonstration was to evaluate SAR as a tool for high-productivity munitions response site characterization (Foley et al., 2007a) through the delineation of areas of potential MEC contamination. Sky Research reengineered existing SAR technology into a new SAR system (denoted as SkySAR) that is a functional ultra-wideband SAR system (230–400 megahertz [MHz]) capable of collecting accurate and repeatable data. The SkySAR data collected for this demonstration were of high quality with moderately low noise characteristics, and were spatially accurate, predictable, and repeatable. The SAR images produced were of an output pixel size of 0.5-m provided by an oversampling factor approximately 30% finer than the nominal 0.7- by 0.7-m resolution. Viable methods of data fusion were developed to significantly reduce vegetation false alarms and are suitable for production-level implementation.

Multiple passes over each imaged area were required during data collection to ensure detection of objects of interest; eight passes were used in this demonstration. The system was capable of detecting surface targets of interest of sufficient size, including simulated ordnance, emplaced targets, and in situ targets. However, the size of items that can be reliably detected by SAR was found to be limited to relatively large items on the ground surface. For the Pueblo demonstration site areas evaluated in this demonstration, metal objects about 30 centimeter(s) (cm) across were found to be detectable in the SAR data, and single metal objects smaller than about 15 cm in diameter disappeared in the clutter. Therefore, the use of SAR will be most applicable to sites with fairly large munitions or munitions scrap on the ground surface. In addition, SAR needs to be used in conjunction with a suite of WAA sensors for target/clutter discrimination to reduce the false alarm rate (FAR). Finally, processing and analysis of SAR data sets is not yet an automated process and, consequently, can be time-consuming and labor-intensive.

HSI sensors were also deployed from fixed-wing platforms as part of the high airborne data collection and analysis for WAA. The HSI data for this project were acquired at spatial resolutions of 1.5 and 3 2/pixel. HSI data collection augmented the analysis of SAR in a multiple-sensor fusion process to reduce the FAR through the generation of detailed vegetation models used to discriminate metal from vegetation in SAR surface object detections. It was found that the 1.5 m2 spatial resolution data was needed for vegetation modeling.

In addition, the use of HSI imagery for detecting and extracting large munitions-related features such as target aiming features and detection of landscape disturbance patterns, including surface disturbance features difficult to observe in other datasets, was evaluated. Although the HSI sensor alone would not outperform the LiDAR/orthophotography sensor combination for general

WAA site characterization, the HSI imagery was found to be useful in detecting some large features obscured in other remote sensing datasets. Last, HSI imagery was also evaluated with respect to the direct detection of metallic objects such as munitions and munitions scrap. The use of hyperspectral data to detect surface concentrations of metal materials depends on the size and spectral characteristics of the metal objects to be detected as well as the spectral characteristics of the background against which they must be detected. At the demonstration site, background soils with abundant iron content made direct detection of surface metal concentrations using HSI problematic. The final report for the HSI demonstration provides a quantitative analysis of this phenomenological issue and recommendations regarding the spatial and spectral resolution requirements and detection phenomenology parameters necessary to make direct MEC detection with HSI useful in a WAA scenario (Foley et al., 2007b).

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

2.1.1 SAR

The SAR technology utilized on this demonstration project by Sky Research is a redeveloped and refurbished ultra-wideband, ultrahigh-frequency (UHF) radar system based on the DoD FOLPEN III system developed by Stanford Research Institute for the Defense Advanced Research Projects Agency (DARPA) in 1993 (Kerner, 1999). Sky Research obtained this system from the Naval Surface Warfare Center, Dahlgren Division, began upgrades in September 2004, and deployed the reengineered SkySAR in May 2005. The number of system redesigns was limited by this 7-month development effort; consequently, SkySAR was developed as a proof-of-principle SAR with limited automated and user programmable operating functions.

2.1.2 HSI

The first airborne image spectrometer was deployed by the National Aeronautics and Space Administration (NASA) in 1985. The first commercially available HSI was the compact airborne spectrographic imager (CASI) in 1989. Since then, HSI has been used in environmental mapping applications to define surface features such as plant species, soil types, and moisture content (Ritter et al., 1996) by imaging and analyzing surface features over a wide spectral band using advanced charged coupled device (CCD) sensor technology and imaging spectrograph optics.

The HyMap HSI technology used for this demonstration has been in commercial and scientific use for geological resource mapping, environmental monitoring, agriculture, and various research applications since 1999. In 2000, Sky Research used HSI technology to discriminate vegetation in SAR datasets at the Former Lowry Bombing and Gunnery Range (FLBGR) near Aurora, Colorado; however, the Pueblo demonstration is the first attempted use of an HSI sensor to directly detect ferrous surface metal for MEC site characterization and the first successful use for detecting munitions target features not visible in conventional orthophotography or high-resolution topographic data.

2.2 TECHNOLOGY DESCRIPTION

2.2.1 Aircraft Platforms

For this demonstration, both sensors were mounted on fixed-wing plane platforms. The SkySAR was installed in an equipment pod on the Sky Research Jetstream 31 aircraft (Figure 1). The HSI sensor was deployed on a DHC-6/300 Twin Otter aircraft.

Figure 1. The Sky Research J31 Aircraft Was Used for All Aviation Activities for SAR Data Collection. (The Equipment Pod [lower-left] Houses the Bi-Static Horns Antenna [right].)

2.2.2 SAR Technology

Deployed from a fixed-wing platform, SAR technology measures round trip travel time and strength of pulsed microwave signals emitted by a radar antenna and reflected off a distant surface or object. An image is built as pulses are emitted, returned, and recorded along the flight line of the aircraft. SAR data can be processed in several ways, yielding different data products. Single polarization data allow creation of 2D images. Multiple polarization data allows more detailed discrimination of different surface types or targets. Interferometric processing allows creation of a digital elevation model (DEM).

The functional capabilities of SAR to detect surface munitions or other metal targets of interest are dependent on the size of the target and the radar's angle of illumination of the target. Atmospheric conditions such as clouds, rain, or fog do not significantly reduce SAR capabilities. However, the degree and type of vegetation on the site and topographic setting of the scene introduces factors that can attenuate, scatter, or misposition the SAR returns. The separation of SAR signals originating from surface and subsurface metal from those generated by vegetation or topographic effects represents a major challenge to SAR in this application.

2.2.3 HSI Technology

The HSI system used in this demonstration was a HyMap operated by HyVista Corporation of Sydney, Australia. While a number of airborne imaging spectrometers exist and the technology is in active commercial use for a variety of geological and vegetation mapping efforts, the HyMap sensor offered the best available combination of spectral and spatial resolution, signal-to-noise ratio (SNR), and geospatial accuracy necessary to achieve the demonstration objectives. However, it should be noted that use of the HSI data for vegetation modeling for SAR false alarm reduction was found to be labor-intensive.

The HyMap is an airborne hyperspectral sensor that measures the electromagnetic spectrum from 0.45 micrometer (µm) to 2.5 µm in 126 separate but contiguous bands that have variable widths (from 15 nanometers [nm] in the visible wavelengths to 17 nm in the short-wave infrared [SWIR] wavelengths). HyMap records an image by using a rotating scan mirror that allows the image to build line by line as the aircraft flies forward. The reflected sunlight collected by the scan mirror is then dispersed into different wavelengths by four spectrometers in the system. The spectral and image information from the spectrometers is digitized and recorded on tape. The many contiguous bands of a hyperspectral imager produce complete spectral signatures associated with each recorded pixel (Figure 2) that allow for identification of materials rather than simple discrimination afforded by most space-based remote sensing instruments (e.g., Landsat) or airborne multispectral instruments. Figure 3 shows the reflectance spectrum for several different classes of materials as a function of wavelength over the bands (spectral analysis conducted on Pueblo 1.5-m resolution data).

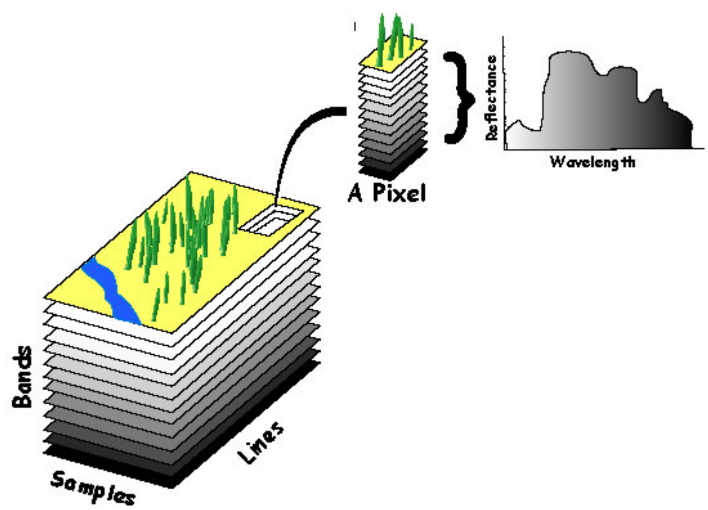

Figure 2. The General Hyperspectral Imaging Concept (measurement of reflected electromagnetic radiation across many tens of contiguous bands where each pixel contains one complete spectral signature used to absolutely identify surface materials)**.**

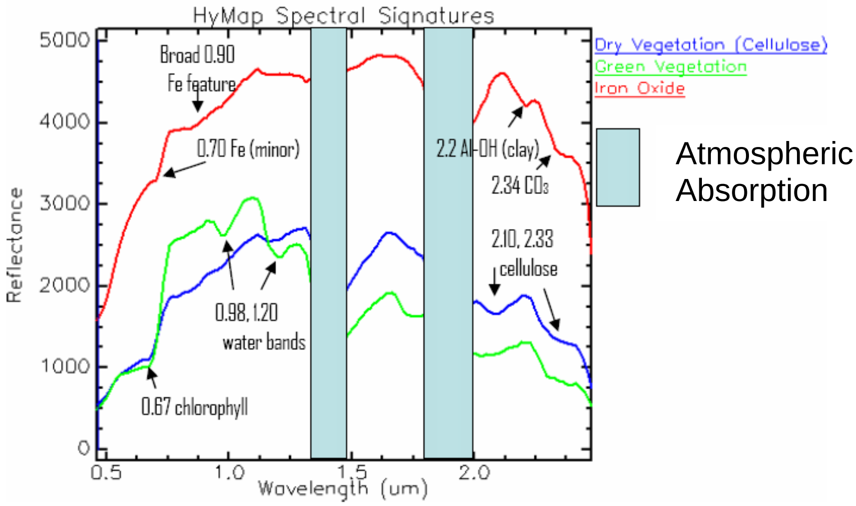

Figure 3. HyMap Spectral Signatures (126 bands) for Three Material Groups of Interest—Dry Vegetation, Green Vegetation and Iron Oxide (important absorption features indicated, and atmospheric absorption regions shown in blue)**.**

To minimize distortion induced in the image by aircraft pitch, roll, and yaw motions, the HyMap is mounted in a gyro-stabilized platform. While the platform minimizes the effects of aircraft motion, small image distortions remain. These residual motions are monitored with an inertial measurement unit (IMU). Dedicated geocorrection processing restores the full geolocation information and allows the creation of geographic information system (GIS)-ready products.

2.3 PREVIOUS TESTING OF THE TECHNOLOGIES

DARPA collected SAR data at a site where emplaced munitions items simulated regions of relatively high target density. Despite the fact that the DARPA SAR system was designed for sensing tanks in foliage rather than for high-density MEC, the munitions-sensing results were encouraging (Carin, 2002). Specifically, models developed by Duke University predicted signatures that were in close agreement with what DARPA measured, and the Duke segmentation algorithms delineated high-density MEC regions from foliage.

ESTCP provided funding to the U.S. Army Engineer Research and Development Center to determine the feasibility of using the foliage penetration (FOPEN) SAR system to measure MEC target signatures in various settings with a secondary objective of determining if the FOPEN SAR has applications for MEC range delineation (Simms, 2003). The FOPEN system was found to be capable of imaging the larger targets; groups of surface 155-mm projectiles were observed but individual items were not. The bandwidth of the UHF portion of the UHF-VHF FOPEN SAR at 200-500 MHz was similar to the SkySAR operating range of 230-440 Mhz, and the radar cross section (RCS) obtained by the FOPEN processing methods (designed to use both the UHF signal and a companion VHF SAR signal to detect vehicle-sized objects under a tree canopy) were suitable for detecting only clusters of 155-mm-sized objects. Sky Research collected SAR data at FLBGR in Colorado. Unfortunately, much of FLBGR was surface cleared prior to SAR collection, and therefore this dataset did not allow consideration of WAA of high-density MEC

regions, although the processing results did provide proof-of-concept for the Bayesian fusion architecture.

The basic HSI data collection technology used for this demonstration has been well established by HyVista. Prior to instrument deployment in this demonstration, specifications and sample datasets for this individual instrument were examined and compared with HSI data collected with other instruments for previous Sky Research projects.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGIES

The primary advantage of using an airborne-based system in general is the ability to acquire a large amount of data covering a wide area in a relatively short period of time. Data collection for thousands of acres for site evaluation takes a matter of days, as compared to the much longer time frame for collecting ground-based data. SAR was found to detect surface metal, but was limited by the size of the items of interest that were detected and by false alarms.

The main advantage of HSI is in generating highly detailed infrared (IR) + visible reflectance spectral data for individual geolocated pixels on the ground surface. Because these spectra are highly correlated with chemical composition, HSI data can be used to create vegetation models for SAR false alarm mitigation; to identify soil and vegetation disturbance patterns that can be caused by munitions impacts; and possibly to identify metallic munitions components and chemical salts in the soil. However, HSI technology is limited by spatial and spectral resolution and geocorrection accuracy.

Both SAR and HSI datasets are large and complex and thereby cost- and labor-intensive to process and analyze. In addition, they require the information technology infrastructure to manage, process, and store the data. These limitations are expected to diminish as new or improved technologies are developed in response to the rapidly growing market for high-resolution geospatial data in a broad spectrum of applications and as computing resources continue to expand in speed and power.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

Performance objectives are critical demonstration components because they provide the basis for evaluating the technology performance. For these demonstrations, performance criteria were established and documented. The SAR-related performance criteria were as follows:

- Horizontal accuracy of the SAR geocorrected and coregistered imagery relative to established ground control
- System noise level quantification
- SAR response characteristics of emplaced simulated munitions targets
- SAR response characteristics of in situ items (metal and vegetation) surveyed within the calibration areas.

For HSI, the primary performance objectives relate to the attainment of resolution and coverage specifications for the basic HSI data collection. Secondary performance objectives relate to the contribution HSI datasets provide to the WAA process, including:

- Mitigation of FAR in the SAR data through contribution of spectral information to a multiple-sensor vegetation model
- Detection of bombing target features and other large munitions-related features
- Detection of surface concentrations of munitions-related metallic materials.

3.2 TEST SITE SELECTION

Pueblo PBR #2 was initially selected for the MM-0416 demonstration of remote sensing technologies in 2004 (SAR, HSI, LiDAR, and orthophotography) based upon site characteristics that were expected to be amenable to metal and feature detection in high airborne remote sensing datasets. When ESTCP created the WAA pilot program in 2005 in response to the DSB Task Force report and Congressional interest, Pueblo PBR #2 was selected as one of the first demonstration sites. Consequently, the demonstration area for Pueblo PBR #2 was expanded and a second data collection conducted in 2005. This second data collection included collection of HSI, LiDAR, and orthophotography datasets and encompassed a second documented bombing target and a suspected bombing target within the demonstration site boundaries (USACE, 1995).

3.3 TEST SITE HISTORY/CHARACTERISTICS

Pueblo PBR #2, located in the southern part of Otero County, Colorado, was used as a World War II-era military training facility. Within the 105 square-mile (67,770 acres) FUDS, the 7,500-acre WAA demonstration area encompasses the two bombing targets (BT3 and BT4) and the suspected 75-mm air-to-ground target area documented in the Archive Search Report (ASR) (USACE, 1995) and shown in Figure 4. Munitions that have been found on Pueblo PBR #2

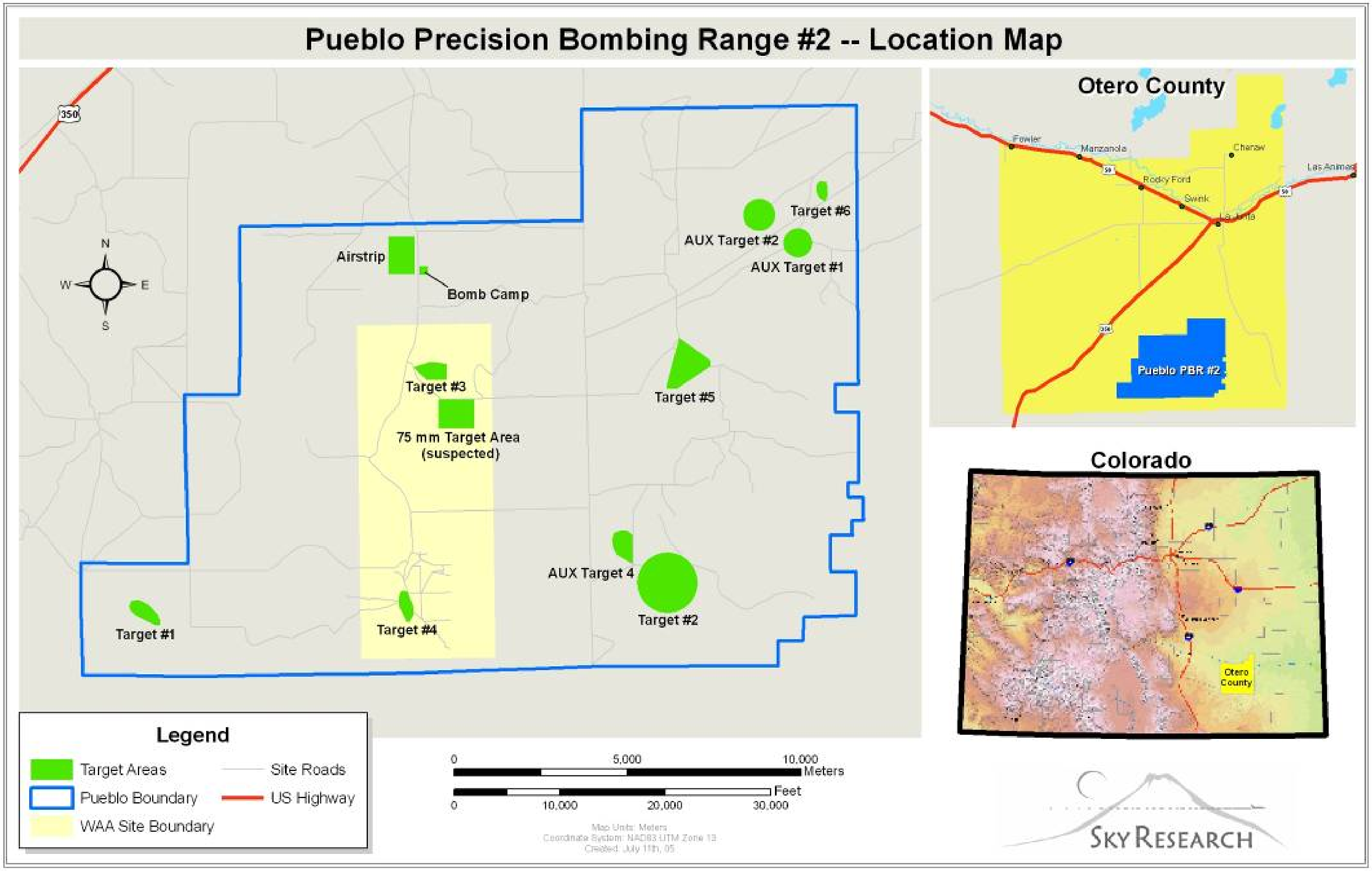

Figure 4. The WAA Demonstration Area (in yellow) Was Located Within the Former Pueblo PBR #2 in Otero County, Colorado.

Munitions Response Area (MRA) and were documented in the ASR include 100-lb general purpose and practice bombs, 75-mm shot, and 50-caliber small arms ammunition (USACE, 1995). The boundaries of the HSI data collection and the SAR imagery output areas are shown in Figure 5.

Land within the study area is primarily in federal ownership managed by the U.S. Forest Service as the Comanche National Grasslands with portions leased to private owners or owned by the State of Colorado. Somewhat less than 2,000 acres of the study area are privately owned, nonresidential grazing lands.

Although initially considered to be a benign site for SAR and HSI data collection due to relatively simple physiography and sparse vegetation, the site provided a more challenging demonstration environment. First, vegetation was an issue with respect to SAR false alarms. Due to the relatively dry climate, prairie grass, and succulent desert vegetation (including yucca, cholla and prickly pear cactus, juniper, and pinyon pine trees), as well as other species of woody or succulent vegetation are present at the site. Plants with taproots, such as yucca, have high water content that can generate SAR responses and cause false alarms. Second, surface metal detections using HSI were not possible. Modern spectral processing methods can achieve materials detection using sub-pixel techniques for materials that consist of as little as 10% of a pixel; however, this requires sufficient spectral contrast between the target material and the background. At the demonstration site, the abundant iron content of the background soils did not provide enough spectral contrast for identifying iron.

3.4 PHYSICAL SETUP AND OPERATION

3.4.1 Mobilization/Demobilization

Mobilization and demobilization for these demonstrations required transport of the plane, equipment, pilot, and sensor operators to and from the base of operations. Ground personnel deployed from Denver, Colorado, to establish ground fiducials, establish and operate global positioning systems (GPS) base stations, and provide logistical support were returned to Denver at the conclusion of the demonstrations.

3.4.2 Calibration Areas

Two discrete calibration sites were established in the vicinity of the BT4 area. The In Situ Calibration Area was a 90x112-m (2.46-acre) area with known occurrences of surface munitions debris. Prior to data acquisition surveys, coordinate data was collected in this area for all vegetation, rock, surface metal, and microtopographic features. The Simulated Ordnance Calibration Area was a 108x137-m (3.67-acre) area with typical vegetation and terrain without previously known munitions debris. Twenty-eight metallic items that varied in size, shape and material to simulate intact munitions objects (sizes ranging from approximately 13-in x 3-in to 60-in x 18-in) were emplaced on the ground surface in this area as calibration items.

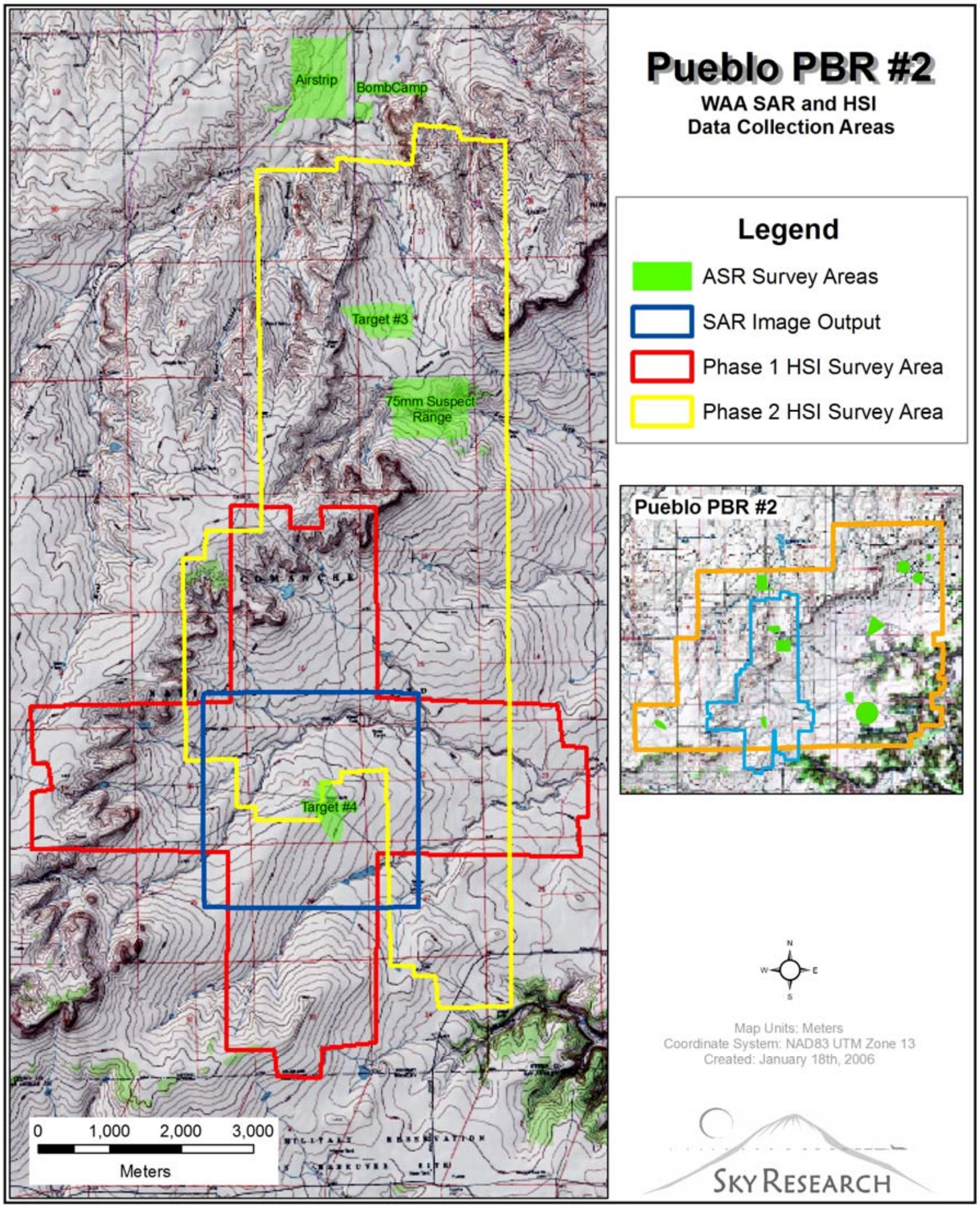

Figure 5. HSI Survey Boundaries and SAR Image Output Areas at Pueblo PBR #2.

3.4.3 Ground Control/Positioning

3.4.3.1 SAR

Triangular-plate trihedral corner reflectors and top hat fiducial targets were used for ground control at the site. Geographic coordinates of these locations were obtained by a licensed surveyor using real-time kinematic GPS (RTK GPS). Two RTK GPS base stations were operated during the data collection survey. Onboard positioning was achieved with an integrated position and orientation (POS)-AV system with post-processed dual channel RTK GPS.

3.4.3.2 HSI

No separate ground control was used during HyMap surveys. All spatial correction information was collected on board the aircraft using a C-MIGITS II IMU, and geocorrections were accomplished post-survey using the GPS information collected during the mission. An assessment of geolocation accuracy indicates that the basic accuracy achieved was on the order of 1-1.5 pixels. Additional geocorrection using control tie points from the orthophotography was completed to increase the spatial accuracy of the HSI data for spectral sharpening of the high-resolution orthophoto and LiDAR datasets, as well as for the vegetation modeling conducted for SAR FAR mitigation.

3.4.4 Navigation Systems

An Applanix A/V POS system was co-mounted with the SkySAR to record the aircraft's GPS position using a dual frequency GPS receiver and attitude (pitch, roll, and yaw) applying an IMU. A customized pilot guidance system was used for flight navigation.

3.4.5 Period of Operation

Test flights of the SAR system were conducted in April of 2005. SAR data acquisition flights were conducted between April 30 and May 6, 2005, as conditions allowed during intermittent periods of clear weather. Data processing and analysis were conducted in 2005 and 2006.

HSI data was collected on September 17, 2004, and August 30, 2005. Data processing and analysis of the 2004 HSI data were conducted in 2004 and 2005. Data processing and analysis of the 2005 data were conducted in 2005 and 2006.

3.4.6 Operating Parameters for the Technology

The SkySAR data collection parameters and sensor parameters are provided in Table 1 and the HSI data collection parameters in Table 2.

Table 1. SkySAR Data Collection and Sensor Parameters.

Parameter	Value	Units / Notes
Flight speed	150	knots
Flight altitude	1,000	m above ground level (AGL)
Swath width	1	kilometers (km)
Frequency	230-440	MHz
Transmitted power (peak)	250	watts (W)
System noise figure	5.0	decibels (dB)
Look angle	30-60	degrees
Ground pixel size	0.7 X 0.7	m
Operation duration	11	hours
Total area	27,455	acres
Number of look directions	8	NS, NS, EW, WE, NE, NE, SW, NW
Effective coverage	3,432	acres/hour

The total area is the number of acres surveyed in each of the 8 look directions. The demonstration area was approximately 2,225 acres.

Table 2. HSI Data Collection Parameters.

Parameter	Value	Units / Notes
Flight speed (1.5-m resolution)	82	knots
Flight altitude (1.5-m resolution)	600	m AGL
Flight speed (3-m resolution)	100	knots
Flight altitude (3-m resolution)	1,200	m AGL
Swath width	1	km
Instantaneous field of view (IFOV)	2.5	millirad (mrad)
Field of view (FOV)	61.3	degrees
Wavelengths	0.45 – 2.5	μm
SNR	>1,000:1	
Total area – 2004 data collection	6,710	acres
Total area – 2005 data collection	9,628	acres (includes an overlap of 3,004 acres of data collected in 2004)

3.5 ANALYTICAL PROCEDURES

3.5.1 SAR Data Processing and Analysis

POS and the RTK GPS data are parsed to create input vectors for image formation. Image formation includes range compression, motion compensation, and azimuth compensation steps (Foley, 2007a). Secondary processing activities included converting the georectified SAR imagery from binary complex data files to georeferenced image files, assessing spatial accuracy relative to ground reference fiducials, performing any required coregistration, and integrating the imagery into the project GIS framework. Figure 6 provides a flowchart overview of the image formation process. Appendix A shows the SAR imagery for the entire Pueblo demonstration area.

Spatial accuracy was assessed by determining spatial offsets between precision top hat fiducial locations and the peak amplitude locations of the corresponding feature in each SAR image.

Targets were selected in a modeling process by combining eight coregistered cardinal pass direction images into a single image using a maximum operation, where targets were extracted

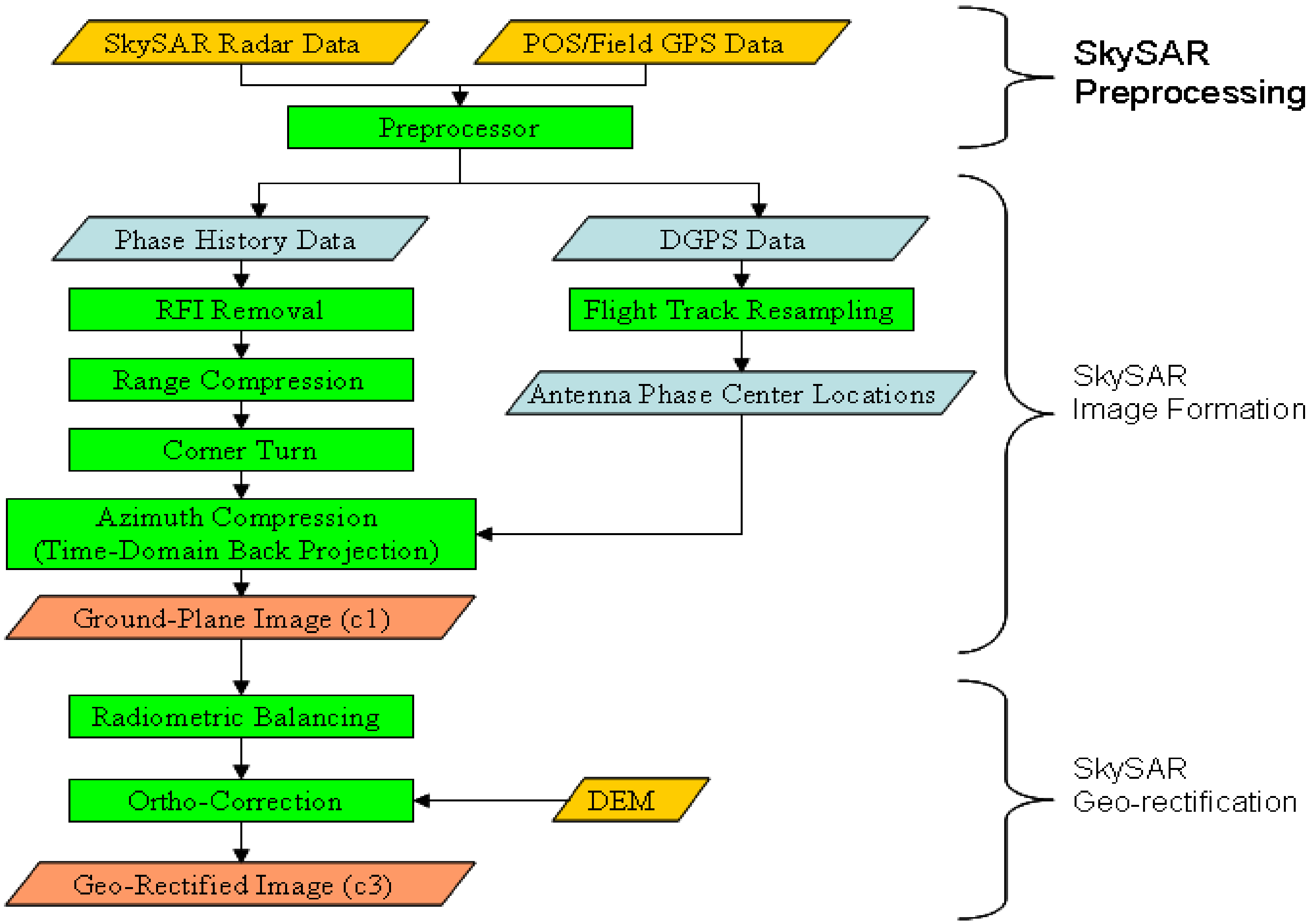

Figure 6. SkySAR Data Processing Flow Schematic.

based on an amplitude threshold operation on the combined image. Target locations were then computed based on the centroid of the thresholded amplitude region, and target morphology attributes were also computed from the thresholded "slice" region in the modeling environment.

To maximize the potential to utilize SAR in WAA, differentiation between suspected MEC (metal) and naturally occurring clutter (frequently vegetation) was needed because both metal and clutter have the potential to exhibit high energy SAR responses. Figure 7 provides a schematic diagram of this process. The two-stage classification system included a front-end pre-screener to support moderate-to-high surface MEC detection rates while providing good false alarm mitigation. The prescreener compared the SAR response from each of the simulated ordnance items to background response in the vicinity, serving to identify points of interest (POI) for further processing by a multisensor, multifeature classifier designed to significantly suppress false-alarm rates to support WAA requirements.

3.5.2 HSI Data Processing and Analysis

A variety of software packages were used for processing the HSI data (Foley, 2007a). The processed HSI data were used for vegetation modeling, detection of surface metal, and detection of munitions-related features. To analyze the HSI data, ENVI Minimum Noise Fraction (MNF) transformations (principal components-based algorithm) were run on all 1.5-m resolution flightstrips, converting the 126-band reflectance data to reduced band sets of 20 eigenbands. These MNF images were then geocorrected using the geographic lookup table (GLT), and converted to band sequential (BSQ) raster format for use in the ArcGIS visualization and feature extraction environment. Band combinations were mapped to the red-green-blue (RGB) image rendering channels after determining which bands and band combinations provided the best feature visualization for detecting known target features. The entire site was then systematically reviewed using single bands and band combinations, in conjunction with other imagery derived from LiDAR and orthophotography datasets.

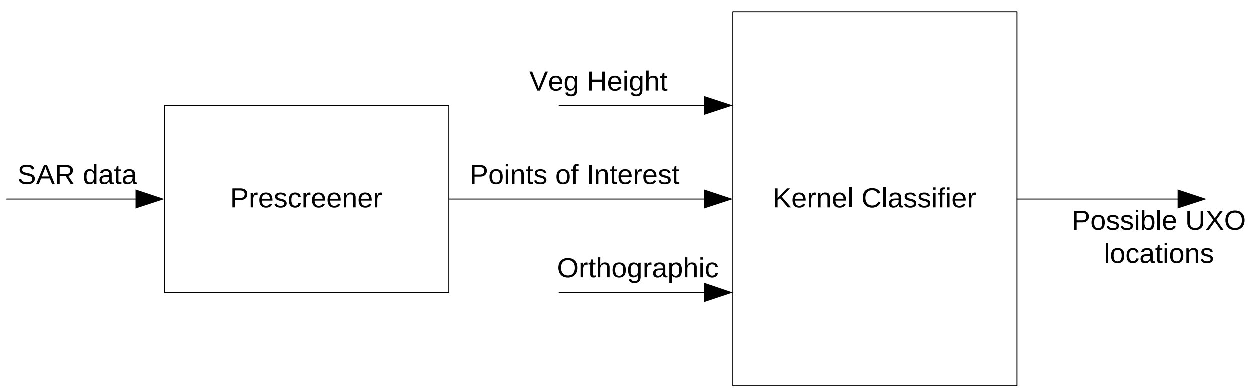

Figure 7. Two-Stage Classification System Included a Front-End Prescreener to Support Moderate-to-High MEC Detection Rates While Providing Good False Alarm Mitigation.

3.5.3 Vegetation Modeling

Vegetation modeling was conducted using HSI data in conjunction with LiDAR and orthophotography data for the SAR analysis to generate feature detections for specific vegetation types that cause false alarm detections in the SAR imagery. Models of the spatial distribution of these plants were then used to discriminate vegetation-caused SAR detections from those caused by metallic objects. The HSI final report provides more information on vegetation modeling methodologies (Foley et al., 2007a).

3.5.4 Data Fusion

Multiple-sensor data fusion is a key element in the successful assessment of surface metal patterns with SAR technology. Data fusion was performed at several levels of abstraction within the WAA analysis for this demonstration, including 1) image-level fusion of HSI, LiDAR, and orthophotography data to extract vegetation features (as described above); 2) image-level fusion of optical and SAR imagery from multiple look directions to prescreen and full, image-based classifiers that predict the image positions of metallic signal generators; and 3) abstraction of spatial models that overlay classified object detections from the various datasets and image-based classifiers to delineate the geospatial patterns of metal object detections weighted by classification certainty and filtered by false alarm object detections. The HSI and SAR final reports provide more information on data fusion methodologies (Foley et al., 2007a and 2007b).

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4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

Primary performance criteria included the qualitative assessment of the ease of technology usage and the quantitative assessment of positional accuracy and resolution of both datasets. Secondary performance objectives considered the contribution of HSI to the WAA efforts, including SAR FAR mitigation through vegetation modeling, the detection of surface metal, and the probability of detection (Pd) of target features and other large munitions-related features. Performance data are provided in Tables 4 and 5.

4.1.1 Spatial Accuracy

The spatial accuracy assessment SAR imagery was performed by comparing image target locations with the corresponding top hat fiducial locations defined by precision GPS coordinates determined when the fiducials were placed. Table 3 provides summary statistics of these accuracies. By registering eight cardinal pass-direction images per tile to the orthophotography and to each other, the horizontal error in the SAR data was improved to less than 1 pixel (0.25-m). This level of spatial accuracy is able to support SAR target discrimination using LiDAR, orthophotography, and HSI auxiliary sensor data.

Table 3. Summary of SAR Radial Error and Post-Registration Residual Errors.

Seven SAR Look Directions	Average (m)	Standard Deviation (m)
Y root mean square error (RMSE)	0.18	0.06
Y linear error (95%)	0.36	0.12
X RMSE	0.23	0.09
X linear error (95%)	0.45	0.18
RMSE horizontal radial error (68.3% confidence)	0.30	0.06
Horizontal radial error (95% confidence level)	0.50	0.12

Spatial accuracy of the GLT-transformed HSI imagery was formally evaluated in a subset of the 21 flight strips by locating the positions of ground fiducial markers in the geocorrected HSI imagery, then computing the X- and Y-offsets from the known GPS location of each marker. Table 6 shows the results of the assessment on three flight strips. While the GLT-processed spatial error was adequate for large-feature detection and characterization, the radial RMSE should be less than 1-m in order for the data to be useful for detecting small metal objects or for fusion processing with SAR, LiDAR, and orthophotography data. Therefore, a principal components spectral sharpening algorithm was used to increase spatial resolution through fusion with the orthophoto image, which successfully increased the HSI image resolution to 0.25-m.

Table 4. SAR Performance Data.

Type of Performance Objective	Performance Criteria	Performance Confirmation Method	Performance
Quantitative	Georeference position accuracy	Horizontal accuracy relative to established ground control	Horizontal error of geocorrected imagery: 0.5-m Horizontal error of coregistered imagery: 0.25-m
	System noise level quantification	Additive noise (NEσ0*): radar equation analysis Multiplicative Noise Ratio (MNR): MNR= 1/clutter-to-noise ratio (CNR)	NEσ0: $\leq$-50 dB MNR: $<$-10 to -14 dB
	SAR response characteristics of emplaced simulated munitions targets on the ground surface within the 3.67 acre simulated ordnance area	Comparison of results to GPS locations	• All simulated target sizes ranging from approximately 13-in x 3-in to 60-in x 18-in detected (all SNR levels) • 85% detection rate with about 60 false alarms using the combined 8-look SAR data
	SAR response characteristics of *in situ* items (metal and vegetation) surveyed within the *in situ* calibration area.	Comparison of results to site visit data of GPS locations of metal and vegetation	• 21% of surface targets detected (at SNR levels of 2.0 or greater) • Rate varied from 84% to about 5% with a corresponding number of false alarms from 1,800 to 80 at SNR thresholds of 5.5 to 1.0 • Detection limit: near the magnitude threshold of about 100 for metal objects with volumes smaller than ~ 10 liters

* NEσ0 = noise equivalent backscatter.

Table 5. HSI Performance Data.

Type of Performance Objective	Performance Criteria	Expected Performance (Metric)	Performance Confirmation Method	Actual Performance Metric Met?
Qualitative (Primary)	Ease of use and efficiency of operations	Efficiency and ease of use meets design specifications	General observations	Easy to use
Quantitative (Primary)	Georeference position accuracy	HSI: 3 – 4.5-m RMSE	Comparison of datasets with ortho-imagery of known accuracy	HSI: 4.9–11.8-m RMSE
	Spatial resolution	2004: 1.5- and 3-m 2005: 1.5-m	Direct examination of the delivered datasets following geo-referencing using supplied GLT files	2004: 1.5- and 3-m 2005: 1.5-m
	Spectral resolution	126 bands (0.45 µm – 2.5 µm)	Direct examination of the delivered datasets following geo-referencing using supplied GLT files	126 bands (0.45 µm – 2.5 µm)
Quantitative (Secondary)	SAR FAR	Reduced FAR	Receiver operating characteristic (ROC) evaluation of FAR	Achieved
	Metal detection of surface metal objects > 1,500 grams	> 0.8	Percentage of metal features extracted from ground calibration and validation datasets detected in HSI	Surface metal detection not achievable at this site
	Detection of target features and other large munitions-related features	> 0.9	Percentage of total large-feature munitions response sites identified in other ground and WAA sensor datasets	0.46

Table 6. Horizontal Accuracy of Selected GLT-Geocorrected HSI Flight Strips.

Accuracy Metric	FL4 (m)	FL5 (m)	FL6 (m)
Y RMSE	11.71	3.00	1.09
Y linear error (95%)	22.94	5.89	2.14
X RMSE	0.99	7.64	4.73
X linear error (95%)	1.94	14.96	9.27
RMSE horizontal radial error (68.3% confidence level)	11.75	8.20	4.85
Horizontal radial error (95% confidence level)	15.54	13.02	7.12

4.1.2 SAR Target Detection

The ability of SAR to detect an object depends on both the RCS of the object and the amount of clutter in the resolution cell. Optimally for target detection, the RCS is large and the clutter is small. RCS depends in large part on the size and shape of the object. It drops rapidly when the object is smaller than the wavelength of the radar signal, and very rapidly when the object is less than about 1/10 of the wavelength; the SkySAR wavelengths range from 0.68-m to 1.3-m. Clutter, on the other hand, is an integrated effect; its signature represents the total energy from all the other items in a resolution cell plus additional radar error. Therefore, based on the SkySAR image noise and resolution characteristics, an object should be detected from any single SkySAR image if its RCS peak amplitude is between 10-14 dB above the surrounding clutter. For this demonstration, this suggests that surface metal objects about 30-cm across should be detectable in the data, and single metal objects on the surface smaller than about 15-cm in diameter will likely disappear in the clutter. This conclusion was supported by data results from the two calibration sites evaluated for this demonstration.

The results of the SAR detection analysis executed from data collected over the Simulated Ordnance Calibration Area are presented in Table 7. A total of 28 simulated ordnance items were emplaced, six of which were placed under cacti to help assess whether such arrangements could be detected by SAR. The results showed that these items could not be used for the SAR processing and image formation methods used for this demonstration. Using the prescreener, a 100% detection rate of the 22 detectable simulated ordnance items was achieved while passing approximately 280 false alarms, with results for a 100% detection threshold illustrated in Figure 8 as a POI overlay on an orthophoto image.

Table 7. Simulated Ordnance Calibration Area Items Detected by SAR.

# of Ordnance Items	Length (m)	Width (m)	Volume (L)
1	1.52	.46	197.30
1	.91	.46	118.33
1	.91	.46	118.33
3	.71	.22	81.00
1	.74	.22	54.01
2	.74	.22	27.01
1	.71	.22	27.01
1	.46	.15	14.79
1	.33	.08	12.09

Table 7. Simulated Ordnance Calibration Area Items Detected by SAR. (continued)

# of Ordnance Items	Length (m)	Width (m)	Volume (L)
1	1.52	.08	6.16
1	1.52	.06	5.87
1	1.24	.06	3.11
1	1.22	.06	2.93
1	1.22	.06	2.93
1	1.09	.06	2.93
1	1.22	.08	2.93
1	1.02	.06	2.77
1	.71	.09	2.35
1	.71	.09	2.35

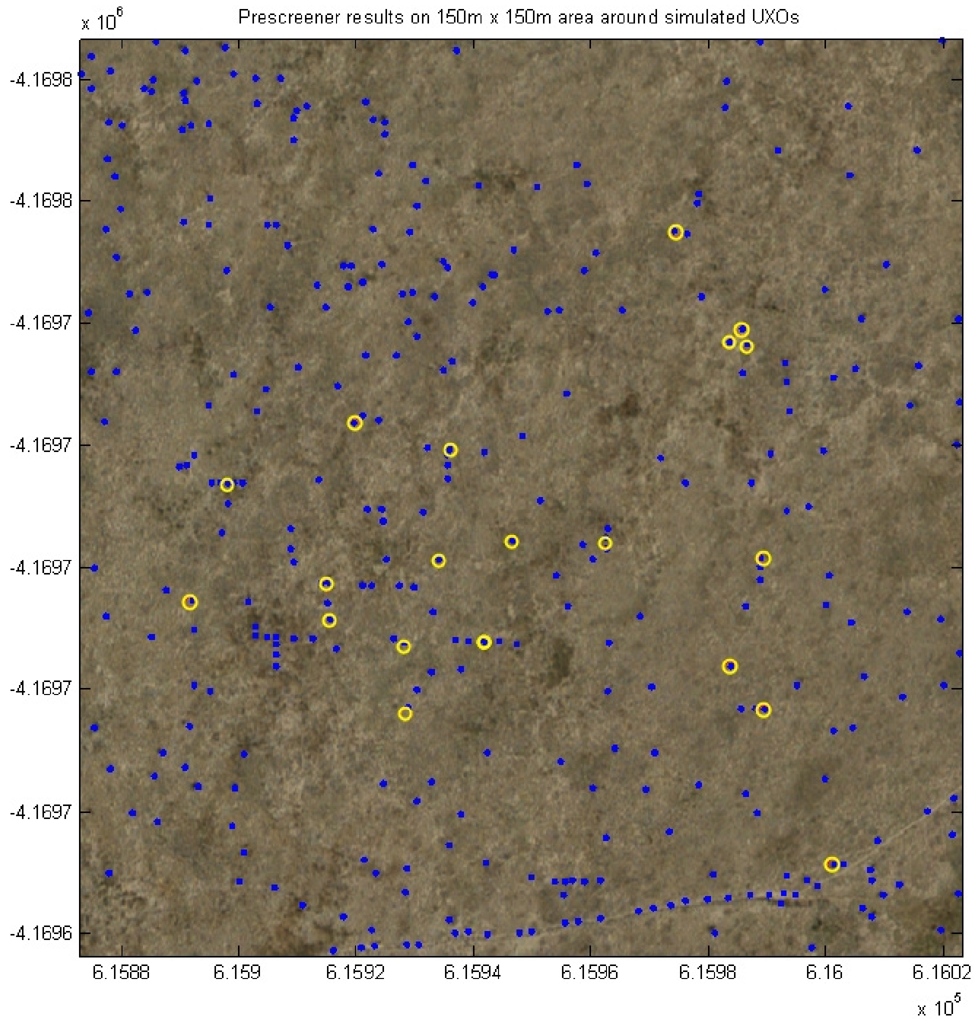

Figure 8. Prescreener Output (POIs) in the Vicinity of the Simulated UXO, at Probability of Detection (Pd) = 100%. (Simulated UXO locations are identified by yellow circles; prescreener POIs are displayed as blue points.)

Table 8 lists the metal objects in the in situ calibration area that were detected; the remaining 23 metal objects known to be present in the area (as documented in a site visit to the area) were not of sufficient size or SNR level to be detected by the SAR technology.

Table 8. In Situ Metal Objects Detected by SAR.

Length (m)	Width (m)	Volume (L)
0.40	0.20	24.0
0.30	0.30	18.0
0.30	0.20	18.0
0.46	0.28	16.7
0.25	0.25	15.6
0.30	0.30	13.5

A set of ROC curves for the two calibration areas was developed to investigate target detection and FARs in the SAR imagery versus known metal calibration objects (Foley et al., 2007b). To execute this analysis, the coregistered 8-look SAR imagery was exploited and a single SAR image combining all 8-looks developed. For both the simulated ordnance and in situ calibration areas, the 8-look SAR image significantly outperformed any individual SAR look image. In the simulated ordnance area, an 85% detection rate was achieved with only 60 false alarms (Figure 9). By comparison, a single-look SAR produced about 800 false alarms to achieve an 85% detection rate. Because of the low number of detectable targets in the in situ calibration area, the ROC curves were less useful in describing the results. The detection rate for the six items detectable by the SAR technology varied from 84% to about 5% with a corresponding number of false alarms from 1,800 to 80. Clearly, at low thresholds, the detections were associated with noise in the data.

4.1.3 False Alarm Mitigation

Vegetation modeling results were used to develop discrimination masks. The utility of the discrimination masks were evaluated relative to the developed SAR target datasets to derive suitable index value thresholds for detecting and discriminating vegetation and slope-related SAR targets. Each SAR target was reviewed with respect to each discrimination mask. The ROC curves for the simulated ordnance calibration area showed that more than an order of magnitude reduction in rate was achieved when vegetation masks were utilized (Foley et al., 2007a and 2007b).

4.2 DATA FUSION

In addition to the vegetation modeling results, two additional data fusion results were achieved by exploiting the registered SAR images, orthophoto data, HSI data, ground truth for the simulated metal ordinates, and height of vegetation determined from the LiDAR data. Using the GGobi software system, 2-D, 3-D, and multidimensional scatter plots were viewed in different combinations. For the 3-D and multidimensional scatter plots, the data were rotated about different axes to determine the optimal separation of metal points from the vegetation and dirt clutter. The most successful combination for separating metal objects from the background clutter was adding the orthophoto RGB data and HSI data to the SAR data.

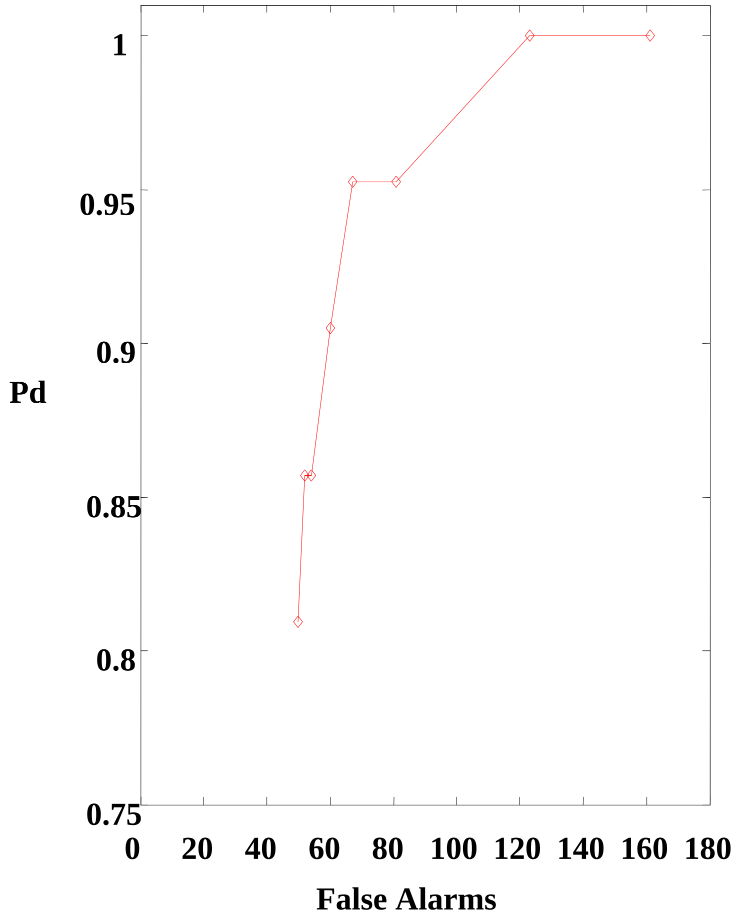

Figure 9. ROC Curve for the Combined 8-Look SAR Data in the Simulated Ordnance Calibration Area.

4.3 HSI DETECTION OF TARGET FEATURES AND OTHER LARGE FEATURES

The strategy of using HSI imagery to detect and map large munitions-related features such as target circles and disturbed ground areas proved to be a useful adjunct to the WAA analysis using LiDAR and orthophotography. The HSI data contributed significantly to the detection and confirmation for two of the five ship targets observed in the vicinity of BT4 because they were topographically obscured in the LiDAR data and very difficult to detect in the orthophotography data (Figure 10).

However, because of reduced spatial resolution and accuracy, HSI data alone would not be a successful substitute for either LiDAR or orthophotography data sets. The summary in Table 9 shows the results using HSI data; the detection rate for ship targets is relatively high and for smaller disturbance features relatively low.

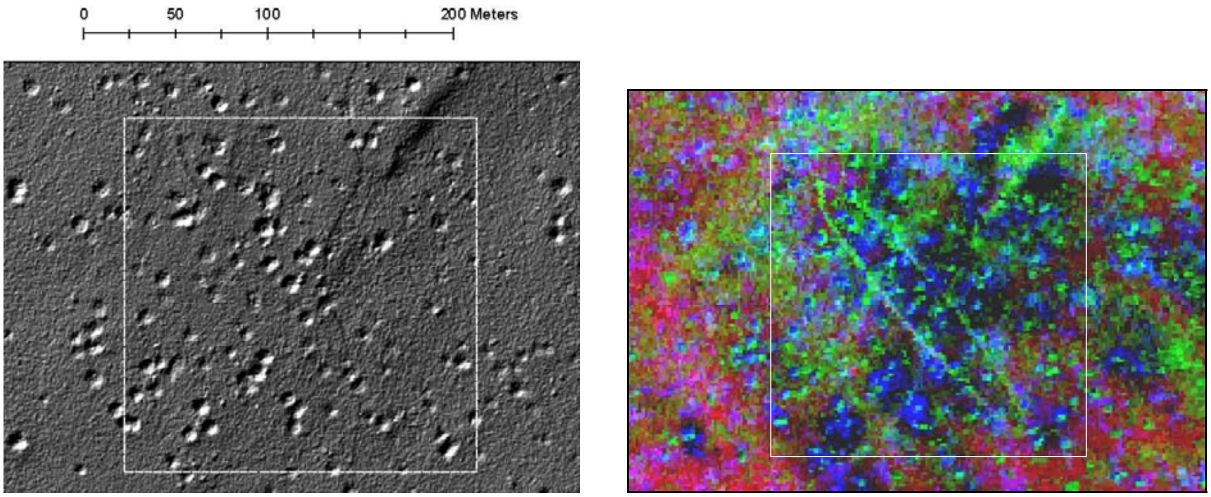

Figure 10. The Ship Target Obscured in the LIDAR Microshaded Relief by Cratering (left) Is Clearly Visible in the HSI Data (right).

Table 9. Large Feature Detection Comparison.

Feature Type	Observed in HSI	Total Features Observed	Percent Detection
Target circles	3	4	0.75
Target crosses	0	4	0.00
Ship targets	4	5	0.80
Other significant features	3	10	0.33
Total large features	**10**	**23**	**.44**

4.4 HSI METAL DETECTION

The calibration studies described did not succeed in using HSI data to directly detect sub-pixel-sized metal features on the landscape surface. Consequently, the surface metal detection objective of the demonstration was concluded with no further site-wide analysis.

4.5 DATA ASSESSMENT

In terms of detection, the developed SAR technology showed robust detection of targets emplaced on the ground surface in the Simulated Ordnance Calibration Area:

- Over 80% of the emplaced targets were detected from a single look-direction; when all look directions were exploited, 100% of all targets were detected.
- Using a SAR image that combines all look directions, 100% detection was achieved with 120 false alarms, which was an order of magnitude reduced compared to single look results. False alarms were reduced to about 60 while maintaining an 85% detection rate.
- The FAR was reduced through data fusion methods that exploited vegetation modeling masks.

However, the results were not as encouraging for the smaller-sized items generally present in the In-Situ Calibration Area. The SAR technology capability demonstrated a detection limit near the magnitude threshold of about 100 for metal objects with volumes smaller than about 10 liters.

Overall, the results indicate that the detection of concentrated munitions debris is possible in areas of low background noise (vegetation, water, or rock facets) and with fragments or munitions near the size threshold for detection. At an appropriate site (such as a dry lake range) that had not been surface cleared, the SAR technology would likely clearly delineate "clean" areas unlikely to have MEC contamination.

For other sites, "density contrast" is a way to characterize the issue of detecting small-item density clusters against a noisy background. In this demonstration, false alarm filtering methods were used to leverage secondary sensors (used successfully at less challenging sites) to detect and eliminate false alarms that were of significantly greater signal magnitude than munitions debris items, but were hampered by the sheer numbers of false alarm generators (primarily cactus) at this site. In addition, if the cactus and other highly SAR-responsive plants were not detected and eliminated and were instead part of the background noise, then the smaller metallic items could not be detected individually. It is unknown and untested what density of small munitions fragments would be required to provide sufficient contrast for detection against a vegetation background like that encountered at the demonstration site, but it may be likely that such concentrations do not commonly occur in actual munitions sites.

HSI was found to be an important dataset for data fusion, primarily the creation of vegetation models for FAR mitigation. In addition, using HSI imagery to detect and map large munitions-related features such as target circles and disturbed ground areas proved to be a useful adjunct to the LiDAR and large-scale orthophotography datasets. Although HSI data alone would not be a successful substitute for either LiDAR or orthophotography datasets, it can play a part in WAA analysis using high-airborne remote sensing techniques. In this demonstration, HSI was not able to be used for surface metal detection due to the lack of spectral contrast between materials of interest and natural landscape materials.

4.6 TECHNOLOGY COMPARISON

The ability of SAR and HSI technologies, both individually and using HSI for false-alarm-reduction, was evaluated for the detection of metal of munitions, and munitions debris was evaluated in this demonstration. The most appropriate technology for comparison is helicopter magnetometry technology.

Because SAR and HSI data can be collected from fixed-wing aircraft at normal flight speed and altitude, these technologies can be used to survey thousands of acres per day. This compares to helicopter magnetometry technology, which can be used to survey on average 400-500 acres per day. In addition, helicopter technology is limited to areas where vegetation, if present, is of limited height (approximately less than 2-m) and to areas without steep topography. Therefore, these technologies may be used in areas where low-altitude helicopter surveys for the detection of munitions would not be feasible. Additional testing and analysis would be required to confirm whether they can be successfully applied at vegetated sites and must take into account the fact that SAR's long wavelengths limit the targets that can be detected. Lowering the threshold to detect munitions and munitions debris would result in a commensurate increase in the FAR. In addition, the data processing, analysis, and fusion techniques used for this demonstration are not

as yet as standard as the processing and analysis techniques for helicopter magnetometry surveys and therefore are more time-consuming and expensive.

5.0 COST ASSESSMENT

5.1 COST REPORTING

Cost information associated with the demonstration of all airborne technology and associated activities was tracked and documented before, during, and after the demonstrations to provide a basis for determination of the operational costs associated with this technology. For these demonstrations, Tables 10 and 11 contain the cost elements that were tracked and documented for this demonstration. These costs include both operational and capital costs associated with the demonstration design and planning; salary and travel costs for support staff; equipment costs associated with aircraft and sensors; support personnel; and costs associated with the processing, analysis, and interpretation of the results generated by this demonstration.

5.2 COST ANALYSIS

The cost of an airborne survey depends on many factors, including:

- Aircraft costs. The rental rate for aircraft costs will be influenced in part by the type of aircraft utilized and the cost of fuel (if included in the cost of the aircraft time). In addition, standby time, if needed, will increase the survey costs.
- Length and number of flight lines required to survey the demonstration area.
- Accuracy requirements, which influence the speed and altitude of the survey flights and the amount of data processing required.
- Location of the site, which can influence the cost of mobilization and logistics.
- Amount of analysis required to sufficiently process and analyze the data.

Costs associated with the ground validation surveys to collect post-survey data were not considered in the cost analysis, as the validation was conducted as part of the WAA pilot program. Also, this demonstration was one of several concurrent demonstrations conducted by Sky Research for the WAA pilot program. Some of the costs associated with management were shared among demonstrations, lowering some of the costs incurred for this demonstration.

Aircraft costs are a major cost factor for any airborne survey. Significant variables and factors associated with the mobilization, data acquisition, and demobilization costs include the cost of aircraft time and standby time. The cost of aircraft can vary depending on the type of aircraft and operating costs. Standby time can also influence the cost of a survey and is typically assessed at the cost of one day of data collection, including aircraft costs, labor, and travel.

Table 10. Pueblo Precision Bombing Range SAR Cost Tracking.[1]

Cost Category	Subcategory	Details	Costs ($)
Start-Up Costs	Predeployment and planning includes—planning, contracting, presurvey site visits	Labor—contracting	21,100
		Labor—planning	178,520
		Labor—site visit	21,720
		Travel	13,226
		Materials and supplies	608
		Subtotal Predeployment Planning	**235,174**
	Mobilization—personnel mobilization, equipment mobilization, and transportation	Aircraft time (2 hours)	5,122
		Aircraft modifications	4,848
		Labor	18,560
		Travel	9,173
		Postage	30
		Subtotal Mobilization	**37,733**
		Total Start-Up Costs	**272,907**
Operating Costs	High airborne survey—data acquisition and associated tasks, including aircraft operation time	Aircraft time (36.8 hours)	94,225
		Equipment	49,346
		Labor	57,392
		Travel	17,653
		Total Operating Costs	**218,616**
Demobilization	Demobilization—personnel demobilization, equipment demobilization	Aircraft time (2 hours)	5,122
		Labor	9,279
		Travel	18,827
		Total Demobilization Costs	**33,228**
Data Processing	Data processing	Labor	120,250
Data Analysis	Data analysis	Labor	109,432
		Supplies and materials	1,030
	Data fusion	Labor	115,301
		Total Data Processing and Analysis Costs	**346,013**
Reporting and Management	Management and reporting	Labor—reporting	40,059
		Labor—management	40,204
		Travel	3,570
		Materials and supplies	220
		Total Reporting and Management Costs	**84,053**
		Total Costs	**954,817**
		Acre Surveyed	**2,225**
		Unit Cost/Acres Surveyed*	**429/acre**

* Note: The unit cost includes the cost for survey flights of the 2,225 acres and the image formation for the survey area. However, only a subset of the survey area data was analyzed (6 acres) to evaluate and demonstrate SAR methodology.

[1] All costs reported for the demonstration include overhead and organization burden and fees.

Table 11. Pueblo Precision Bombing Range HSI Cost Tracking.[2]

Cost Category	Sub Category	Details	Costs ($)
Start-Up Costs	Predeployment and planning—includes planning, contracting, presurvey site visit	Labor	27,053
		Site visit travel	3,428
		Subtotal Predeployment Planning	**30,481**
	Mobilization—personnel mobilization and equipment mobilization	Subcontractor (mobilization of equipment, aircraft and personnel)	11,103
		Labor	4,137
		Subtotal Mobilization	**15,240**
		Total Start-Up Costs	**45,721**
Operating Costs	High airborne survey—data acquisition and associated tasks, including aircraft operation time	Subcontractor (equipment, aircraft and personnel)	37,010
		Labor	7,985
		Materials and supplies	880
		Total Operating Costs	**45,875**
Demobilization	Demobilization—personnel demobilization, equipment demobilization	Subcontractor (mobilization of equipment, aircraft and personnel)	11,103
		Labor	4,137
		Total Demobilization Costs	**15,240**
Data Processing and Analysis	Data processing and analysis, including vegetation modeling	Labor	96,115
		Total Data Processing and Analysis Costs	**83,558**
Management and Reporting	Management and reporting	Labor	52,007
		Travel	14,107
		Total Management and Reporting Costs	**66,114**
		Total Costs	**269,065**
		Acres Characterized	**13,334**
		Unit Cost/Acre Characterized	**20.18/acre**

* Note: 3,044 acres of the 2005 data collection overlapped the 2004 data collection area. The 13,334 acres is the total number of acres characterized.

[2] All costs reported for the demonstration include overhead and organization burden and fees.

Project planning was a significant cost associated with the SAR demonstration because of the need to reengineer the SAR sensor prior to deployment. In addition, due to the unique nature of the demonstration, more planning meetings with ESTCP personnel were conducted than would be typically required of a production-level survey.

Mobilization and demobilization costs are most significantly a function of the distance from the home base for the aircraft. In addition to the cost of mobilizing and demobilizing the aircraft, the cost of mobilizing equipment (sensors and GPS equipment) can add significantly to costs. For these demonstrations, the daily rates for the SAR sensor and GPS equipment were not charged for mobilization and demobilization because each required less than one day. For a mobilization taking a full day or longer, the daily rate for the SAR sensor and associated equipment would have been assessed, increasing the mobilization and demobilization costs. Therefore, for a site requiring a longer mobilization distance, the mobilization and demobilization can take up a correspondingly larger amount of the budget, especially when considered as a percentage of the cost for surveys of relatively small areas.

For the costs associated with the data acquisition flights, the predominant costs are the cost of the aircraft and equipment. The major driver for these costs is the survey size. Fixed-wing aircraft can cover up to approximately 15,000 acres per day on average. Sites less than this in size will therefore be more expensive on a per acre basis. The remainder of costs associated with data acquisition includes labor, travel, and materials/supplies.

Data processing and analysis costs are typically linear with project size. For these demonstrations, the data processing and analysis techniques were still under development, causing the processing and analysis costs to be much higher than would typically be encountered on a production-level survey. In addition, environmental conditions such as the vegetation encountered increased the amount of time needed for vegetation modeling and data fusion. Sites without vegetation would require less analysis. Processing and analysis costs have been decreasing with experience at multiple sites, automation of processing and analysis routines and increased computing power resulting in faster processing.

Project management and reporting were a somewhat significant cost for these demonstrations, as the projects were conducted under the WAA pilot program and required more meetings and reporting than would generally be expected for a production level survey.

5.3 TYPICAL AIRBORNE SURVEY COSTS

Mobilization distance, site size, site conditions, and project objectives can influence the costs of data collection and analysis. In addition, this demonstration utilized a fixed-wing aircraft; different kinds of fixed-wing aircraft will have somewhat different hourly rates than the rates used in this demonstration.

Typical airborne survey costs for SAR would be less than encountered on this demonstration because of the advances in technology since this demonstration was conducted, most notably in the area of data processing and analysis costs. For SAR data collection, data processing, analysis (SAR data only), and reporting of a survey site of 75,000 acres (three days of data collection), the costs would be approximately on the order of $570,000 (or $7.70/acre). Costs for performing

data fusion with additional datasets are not included in this estimate and would increase the cost of a SAR survey if advanced analysis was desired.

5.4 COST CONCLUSIONS

Due to the unique nature of the demonstration and the need to reengineer the SAR sensor, develop and investigate data processing and analysis techniques, and investigate data fusion techniques, the cost per acre for SAR was much higher than for other high-airborne survey technologies. These costs, however, would be expected to be much lower with a more mature system in a production-level survey.

A number of factors should be considered for WAA technology selection, including the acquisition of SAR and HSI data, when evaluating the appropriateness of airborne technologies and potential for cost savings. For effective use of resources, site characteristics should be evaluated to determine the use of appropriate sensors. Site characteristics of concern for the application of SAR and HSI technologies include site size, terrain, vegetation, and contamination characteristics. In sites with vegetation, if SAR is to be used for metal detection, HSI-derived vegetation models will most likely be necessary for false-alarm reduction, increasing costs.

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6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

Because of the need to reengineer the SAR system and develop data processing and analysis techniques to analyze the SAR data, this demonstration was expensive in comparison to better understood and more widely used WAA technologies. However, since the time of this demonstration, Sky Research has further refined the SkySAR system to expand the sensor capabilities and increase efficiency in data processing and analysis. Therefore, the costs to deploy the SAR system would be less than the costs experienced for this demonstration.

6.2 PERFORMANCE OBSERVATIONS

Pueblo presented a challenging site for the demonstration of these technologies due to the vegetation issues (SAR) and chemical composition of the soil (HSI). In addition, as demonstrated, SAR technology can detect metal but is limited by minimum size detections. Therefore, it is important to review and assess the site characteristics and potential munitions contamination and the potential impact conditions such as these might have on the results before incorporating the use of these sensors in a multisensor WAA analysis.

6.3 SCALE-UP

As with all airborne surveys, the use of either technology on very small sites may not be cost effective because of the costs associated with mobilization, demobilization, and minimum operation times of aircraft, therefore, the larger the site, the more cost-effective their use on a per acre basis.

6.4 OTHER SIGNIFICANT OBSERVATIONS

The following are observations from this demonstration and recommendations for continued work with these data:

- *Coregistration*. The coregistration was based on multiple link-points associated with each dataset. While adequate for this analysis, the spatial coregistration process was labor-intensive and can be improved through automated procedures. As use of these data has shown to be essential to reducing the number of false alarms, refinement of this process is recommended.
- *Vegetation model*. The results related to FARs demonstrated the value of the derived site vegetation model based on the fusion of orthophotography, LiDAR, and HSI data. The exploitation of these data can be improved through a more comprehensive analysis, including additional vegetation ground truth data.
- *Site calibration information*. The Simulated Ordnance Calibration Area proved to be very useful for the definition of SAR detection capabilities. However, this area was limited in terms of size, range of site conditions, and number and type of emplaced simulated munitions. To supplement the simulated ordnance data, additional information was gathered from an In Situ Calibration Area.

Unfortunately, this randomly selected area contained few metal targets within the operating wavelengths of the SAR (68- to 130-cm). It is recommended that additional ground truth information related to surface metal distribution be collected and included in the analysis. In the future, a significantly more comprehensive simulated ordnance area should be utilized.

- *Operating parameter optimization*. The ROC curves developed during this project represented the synthesis of numerous data collection, processing, analysis, detection, fusion, and discrimination steps. The optimization of this process is recommended to maximize the ROC curve performance of the technology.

6.5 LESSONS LEARNED

Several lessons have been learned through the execution of this project regarding the use of SAR as a WAA tool applied to former military facilities contaminated with MEC. Significant insights were gained on the following topics:

- The importance of multiple-look SAR spatial registration, their coregistration with companion datasets, and the procedures required to achieve decimeter-level accuracy
- The exploitation of multiple-look SAR data to establish improved detection rates
- The effective and coordinated fusion of SAR data in conjunction with HSI, LiDAR, and orthophotography datasets for the mitigation of false alarms
- The feedback of ground verification information to establish optimal processing parameters used in establishing effective vegetation models, SAR filtering parameters, and multilook SAR SNR thresholds.

6.6 END-USER ISSUES

Implementing WAA for production level surveys should include end users in the project. For this project, ESTCP has been utilizing the WAA Advisory Group to understand and evaluate potential end-user issues and concerns that can impact the widespread implementation of WAA technologies. End users can also be provided on-line access to WAA data and analytical tools through the use of GIS, as demonstrated in the MM-0537 WAA GIS demonstration project.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

The ESTCP Program Office established an Advisory Group to facilitate interactions with the regulatory community and potential end-users of this technology. Members of the Advisory Group included representatives of the USEPA, state regulators, USACE officials, and representatives from the services. ESTCP staff worked with the Advisory Group to define goals for the WAA pilot program and develop Project Quality Objectives.

There will be a number of issues to overcome to allow widespread implementation of WAA beyond the pilot program. Most central is the change in mindset that will be required if the goals of WAA extend from delineating target areas to collecting data that are useful in making

decisions about areas where there is not indication of munitions use. Therefore, the challenge for adoption of a WAA approach with respect to regulatory acceptance may be the collection of sufficient data and evaluation that the application of these technologies to uncontaminated land and understanding the results. Similarly, demonstrating that WAA data can be used to provide information on target areas regarding boundaries, density, and types of munitions to be used for prioritization, cost estimation, and planning will require that the error and uncertainties in these parameters are well understood.

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7.0 REFERENCES

Carin, L., N. Geng, M. McClure, Y. Dong, Z. Liu, J. He, J. Sichina, M. Ressler, L. Nguyen, and A. Sullivan. "Wide-Area Detection of Land Mines and Unexploded Ordnance," Inverse Problems, Vol. 18, pp. 575-609, June 2002.

Foley, J., and C. Patterson. 2007a. *Demonstration of Airborne Wide Area Assessment Technologies at Pueblo Precision Bombing Ranges, Colorado Final Report - Hyperspectral Imaging.* Final Report. September 2007.

Foley, J., and C. Patterson. 2007b. Sky Research Inc. *Wide Area Assessment Using Synthetic Aperture Radar at Pueblo Precision Bombing Range, Colorado*. November 2007.

Foley, J., 2008. *Demonstration of LiDAR and Orthophotography for Wide Area Assessment at Pueblo Precision Bombing Range #2, Colorado*. Draft Final Report. January 2008.

Hodgson, Jerry. USACE, Omaha District "Footprint Reduction, Utilizing Airborne Technologies at the Former Lowry Bombing and Gunnery Range, Colorado": 5th Environmental Technology Symposium & Workshop, Charlotte, North Carolina, March 26, 2003.

Kerner, D., *Anti-Personnel Landmine (APL) Detection Technology Survey and Assessment*, technical report to Defense Threat Reduction Agency, March, 1999.

Defense Science Board (SDB). Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics. 2003. *Report of the Defense Science Board Task Force on Unexploded Ordnance*. 20301-3140. December 2003.

Ritter, Rebecca A., Helen D. Berry, Betty E. Bookheim, and Amy T. Sewell. "Puget Sound Intertidal Habitat Inventory 1996: Vegetation and Shoreline Characteristics Classification Methods," Washington State Department of Natural Resources, April 5, 2002.

Simms, J., *Applications of Synthetic Aperture Radar (SAR) to Unexploded Ordnance (UXO) Delineation.* ESTCP Project, August 2003. U.S. Army Engineer Research and Development Center. ERDC/GSL TR-03-15, August 2003.

Sky Research. 2005a. *Final Wide Area Assessment Report, Former Lowry Bombing and Gunnery Range, Arapahoe County, Colorado,* Submitted to Jerry Hodgson, USACE – Omaha, February, 2005.

Sky Research. 2005b. *Wide Area Demonstration Plan for LiDAR, Orthophotography, Hyperspectral Imaging and Helicopter MTADS at Pueblo Precision Bombing Range #2*. Final Report. August 2005.

United States Army Corps of Engineers, St. Louis District. 1995. *Archive Search Report Findings, Pueblo PBR #2.*

Versar. 2005. *Conceptual Site Models to Support ESTCP Wide Area Assessment.*

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APPENDIX A

POINTS OF CONTACT

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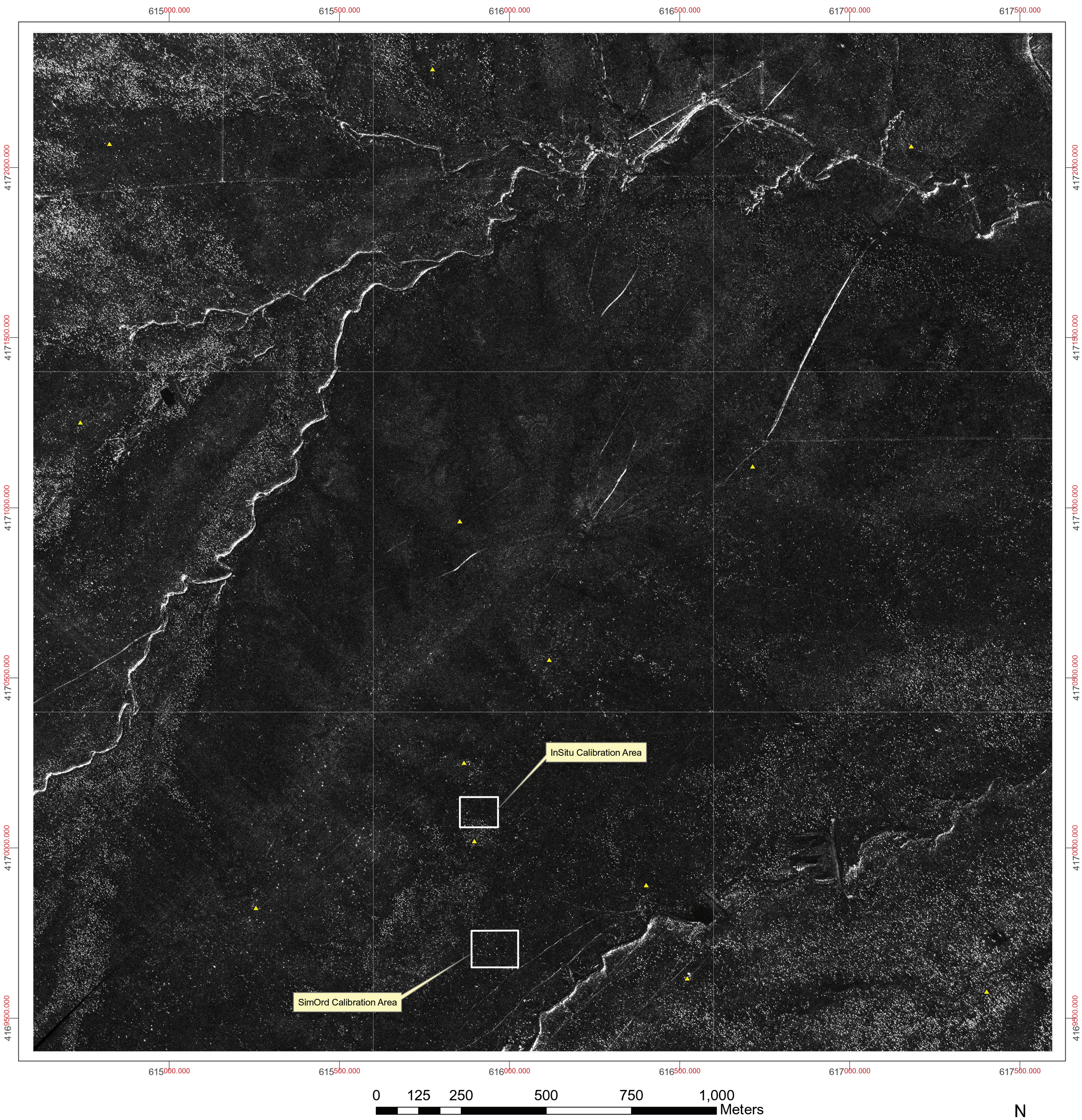
APPENDIX B
SAR OVERVIEW IMAGE OF DEMONSTRATION SITE



Legend

Top Hat / Corner Reflector

505p21C3 Magnitude Image

Value

High : 7816.230957

Low : 0.003693

505p20C3 Magnitude Image

Value

High : 4310.675293

Low : 0.000000

SAR IMAGE OF PUEBLO STUDY AREA

Sky Research

Map Units: Meters

Coordinate System: NAD83 UTM Zone 13

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